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METALURGICKO – STRUKTURNÍ SOUVISLOSTI PŘI ZVYŠOVÁNÍ TRVANLIVOSTI MATERIÁLU PRO PRÁCI ZA TEPLA

METALLURGICAL – STRUCTURAL CONNECTIONS WHILE INCREASING THE DURABILITY OF THE MATERIAL FOR HEAT WORK

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Abstrakt: Příspěvek je zaměřen na výzkum metalurgicko – strukturních souvislostí při zvyšování trvanlivostí materiálu pro práci za tepla modifikací jakosti oceli typu X38CrMoV5-1 (ČSN 41 9552) vyráběných na elektrické indukční peci. Jeden ze způsobů možnosti zvýšení odolnosti proti otěru základní kovové matrice jsou kombinace obsahu prvků zvyšujících odolnost proti abrazivnímu působení tekoucího kovu. Jedná se následně o zvyšování tvrdosti úpravou tepelného zpracování k maximálním hodnotám. Návrh modifikací oceli typu X38CrMoV5-1 vychází ze základního chemického složení úpravou především obsahu uhlíku, molybdenu a wolframu.

Abstract: The paper deals with the research of metallurgical-structural connections while increasing the durability of the material for heat work by modifying steel grade of X38CrMoV5-1 (ČSN 41 9552) type produced in an electrical induction furnace. One possible way of increasing abrasion resistance of the basic metal matrix is different combinations of the content of elements which increase resistance to abrasive action of molten metal. Subsequently, hardness is increased by adjusting heat treatment to maximum values. The proposed modifications of steels of X38CrMoV5-1 (ČSN 41 9552) type are based on the chemical composition by adjusting the carbon, molybdenum and tungsten content.

1. INTRODUCTION

Focus on hot forging die stroke number increasing is one of methods of the production cost reduction in die forges. With the increase of size and shape complexity of forging production series, it is advisable to apply more costly tools with the possibility of a higher number of forged pieces than it is usual with ordinary tool steels of X38CrMoV5-1 type (ČSN 41 9552). Total costs connected with tool replacement and a production line shut-down are critical and prohibitively high then. That is the reason why to search for a solution which would ensure reducing specific costs for manufacture of forging dies that are mainly subject to cyclic impact of high temperature strain during processing. On a tool's surface, the temperature may reach up to 400°C and, furthermore, mechanical stress in form of high specific pressure occurs here. Among the most important forging die material properties there are higher temperature hardness and strength, toughness and resistance to tempering, mechanical and thermal fatigue. Regarding steel chemical composition for thermal resistance, Mo or Ni additives are applied, and also particularly carbide-forming elements, for example chromium, vanadium and wolfram which subsequently increase especially hardness and hardenability. In these steels, those carbide-forming elements content is usually lower than in steels for cold working due to prevention of undesirable decrease of toughness.

What is the most significant is the practical knowledge that tool steels mechanical properties show really substantial differences with regard to insignificant difference of chemical composition. In

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particular, reasons can be found in new production processes and also in the quality of technological – metallurgical secondary metallurgy, of heat treatment ensuring the optimal microstructure for subsequent alloy treatment of steel, and in current observations of the influence of deformation processes managing during manufacture of forgings for forming dies [1].

2. MATERIALS SUITABLE FOR FORGING DIES MANUFACTURE

Generally, basic characteristics of tool steels for forming dies are specified by a standard which defines chemical composition, mechanical and physical properties in relation to heat treatment. Material requirements give a background essential to meet a number of strokes into forging dies. These can be reached besides the basic chemical composition, for example carbon content about 0.35-0.55 %, chromium 3-6 %, vanadium 0.5-1 %, molybdenum 1-2.25%, sulfur max. 50 ppm, also by methods of deoxidation and other secondary metallurgy methods. Further, by precisely limited amount of inclusions and their distribution in metal matrix etc.

Additional requirements for tool steels initial condition, i.e. after spheroidizing state, are defined by some acceptance terms [2]. These terms set requirements for the microstructure in the spheroidized (i.e. initial) condition, the microsegregation processes level, microcleanliness and the original austenitic grain size. All these material characteristics are dependent not only on the method of deformation process control but also on the heat treatment scheme after forging.

Deviations from parameters reguired lower the level of, e.g., toughness, etc. As for tool steels properties, the basic metal matrix character is decisive, namely concerning microstructure homogeneity and fineness and quantity, size and distribution of carbides. These initial state characteristics, i.e. after spheroidizing, are decisive for subsequent refinement and give a background to gain characteristics which influence the forging dies' number of strokes [1].

A fundamental difference with steels applicable for forging dies is given by their application depending on a forming aggregate type.

Dies which are used for *hammer forging* are largely more complicated in shape and they are manufactured from dimensionally larger forgings. Material grade is usually selected from low- and medium alloyed Cr-Ni steels, and also molybdenum or molybdenum and vanadium alloyed. The basic impacts of mechanical and thermal stressing of material are complemented by a typical stress factor, a heavy stroke. A very significant thing is notch toughness value, reported at min. 30 – 40 J/cm^2.

Forging press tools are not exposed to such heavy strokes as it is during hammer forging and, for example, notch toughness required value is about 10 J/cm^2. On forging presses, forgings with thinner walls are manufactured, which are cooled down faster during forming, they increase their strain strength and thus they contribute to the die cavities wear, namely in a fin area. Therefore, higher hardness and strength, which concur at abrasion resistance favourably, are required on dies. Hence, strength values of dies, die inserts and other tools range mostly between 1,600 – 1,800 MPa. Regarding operational conditions, high tempering resistance is essential at large tools as well.
Particular requirements for physical and mechanical properties of tool materials call for broader assortment of recommended tool steels. Predominantly, medium- and high alloyed steels with carbide-forming elements, Cr, Mo, V and W are applied.

3. REASONS FOR DISCARDING DIES

During a forming process, in a die body, on places of contact of formed material and a tool mainly pressure strain occurs [3]. The biggest wear of a die cavity surface is in area of the largest displacement of material during forming. By material forming, stresses emerge which are influenced by a surface condition and a process of reactions on the tool/formed material interface. Among main factors affecting a die's operating life, we can classify die material, design, production method, heat treatment technique and quality, thermal and mechanical stress of a die during forging and forging conditions.

Through operational verification of the examined material of steel grade according to X38CrMoV5-1, which forging die bodies were made from, its continuous standard durability has been confirmed. **Fig. 3.1**, shows damaged basic dimensions of the die's edge parts which were the decisive reason for discarding.

Obr. 3.1 Detailní pohled na opotřebení kovací zápustky
Fig. 3.1 Detailed view of a forging die wear

4. MAKING EXPERIMENTAL HEATS OF X38CRMOV5-1 TYPE MODIFIED GRADES

By valuating obtained results from experimental assessment of operating life of forging dies made of X38CrMoV5-1 material, a conclusion can be made that together with hardness increasing via heat treatment, namely to values close to maximum possible, it is practicable to make use of another method to increase abrasion resistance. The procedure inheres in composition of the basic metal matrix modifications with the aid of elements which increase resistance to abrasive activity of flowing metal in a die's cavity.

Regarding steel chemical composition, the described influence of individual elements on physical and mechanical properties has only general character, it does not solve whole the complex of relations and implications.

MOLYBDENUM increases tensile strength, toughness, yield strength and hot elasticity limit, heat resistance and corrosion resistance. *It decreases* susceptibility to overheating in heat treated steels. It is a ferrite-forming element and a part of molybdenum dissolves in ferrite, the hardness of which is increased and a part of molybden forms carbides. It is used in combination with other alloying elements. It significantly increases hardenability. It decreases temper brittleness and it improves grain fineness and weldability. Deformability decreases with higher molybdenum content. It influences carbide formation and that is why it is used in fast cutting tool steels. It belongs to elements which increase corrosion resistance. A high content increases resistance to pitting corrosion.

WOLFRAM *increases* hardness, strength, yield strength, heat resistance, resistance to tempering. *It slightly decreases* extensibility. It belongs to ferrite-forming elements. In low-alloyed steels it is dissolved in cementite, special carbides are formed at wolfram higher content. It decreases carbon's diffusion speed in ferrite and austenite, thus it decelerates diffusion transformation. A small amount of wolfram increases hardenability more than a big amount. A larger amount supports formation of transition structures and residual austenite. Besides, it decreases resistance to thermal fatigue crack formation. A higher content it decreases toughness and plastic properties of steel. In low-alloyed steels it makes pearlite lamellae liner, thereby increasing strength. Wolfram increases wear resistance and steel cutting property at elevated temperatures, hence it is commonly used element in fast cutting steels, hot worked steels and high hardness steels.

VANADIUM *increases* strength, yield strength, toughness, heat resistance, fatigue strength, annealing temperature during heat treatment. *It decreases* sensibility to overheating during heat treatment. It belongs to strongly ferrite-forming elements. It refines primary graininess and, consequently, also castings structure. It forms very stable carbides with high hardness (up to 2,500HV limit), hence it increases wear resistance. However, it supports hot embrittlement of steels.

Empirical concept included production of three options of X38CrMoV5-1grade modifications. The task was to find such steel chemical composition which, in the final phase, would advance a forging die material durability beyond the reached limit of this material.

Tab. 4.1. shows the content of some elements in experimental heats of modification no.1, no. 2 and no. 3. It broadens the possibilities of X38CrMoV5-1 steel, primare by in the sphere of increased hardness, strength, toughness and wear resistance. Alloying elements combination (coming from similar European and other standards) increases costs but a higher number of strokes to forging dies is expected thus meeting the set aim of the work [4].

Element	Modification Heat no. 1	Modification Heat no. 2	Modification Heat no. 3
C	0.45-0.55	0.55-0.65	0.65-0.75
Cr	4.5-5.5	4.5-5.5	4.5-5.5
Mo	1.1-1.6	0.5-0.8	0.5-0.8
V	0.35-0.60	0.35-0.60	0.35-0.60
W	1.5-2.0	3.5-4.0	4.5-5.0

Tab.4.1 Návrh modifikací chemického složení nástrojových ocelí experimentálních taveb

Tab.4.1. Proposal of chemical composition modifications of tool steels in experimental heats

Individual heats (modification no.1, no.2 and no.3) were processed in an electrical induction medium-frequency furnace (EIPS) with Al_20_3 based lining. The charge basis was returnable scrap from X38CrMoV5-1 type steel grade production and additional alloying was done with the help of clean additives. Tapping temperatures ranged between 1,640 – 1,660°C, the temperature in the casting ladle was 1,590 – 1,600 °C. Partial steel deoxidation in EIPS and final deoxidation in the casting ladle with the aid of aluminium with CaSi charged at the same time to ensure inclusions modification in the steel. Casting of each melt into two pieces of K 208 type moulds. Resulting heat analyses of some elements within experimental heats are shown in **Tab. 4.2.**

The produced ingots were spheroidized in a mode 820 °C/4h/furnace with cooling speed 20 °C/h. Further more from each modified heat one ingot was selected which was forged into a round billet, D = 40 mm. The forging die dimension was chosen so that at least of sixth degree forging was reached [4].

Element	Heat no. 7 analysis, Modification no. 1	Heat no. 8 analysis, Modification no. 2	Heat no. 9 analysis, Modification no. 3
C	0.48	0.59	0.68
Cr	4.85	4.60	4.60
Mo	1.15	0.75	0.72
V	0.42	0.41	0.41
W	1.60	3.55	4.70

Tab. 4.2 Výsledné tavební analýzy některých prvků experimentálních taveb

Tab. 4.2 Resulting heat analyses of some elements in experimental heats

5. ELABORATION OF RESULTS OF ACHIEVED MECHANICAL PROPERTIES WITHIN EXPERIMENTAL HEATS

Forged bars were rough machined and after heat treatment the first tests of mechanical properties were performed. The achieved hardness and notch toughness results at temperature of 20 °C and elevated temperature of 450 °C are shown in **Tab. 5.3** and **Tab. 5.4.**

Heat	Heat treatment, quenching/tempering	Hardness HRC	KCU 2 J/cm^2
7	1,060°C/oil/590°C	56.5	20.3
8	1,060°C/oil/605°C	55	12.7
9	1,060°C/oil/590°C	57	19

Tab. 5.3 Hodnoty vrubové houževnatosti při teplotě 20 °C

Tab. 5.3 Notch toughness values at 20°C temperature

Mechanical properties values are taken as a start for further chemical composition optimization of the grade according to ČSN 41 9552, 19 552 grade (X38CrMoV5-1) ensuring higher abrasive wear resistance.

Looking at results of trial heats no. 7, no. 8 and no. 9 in the sphere of hardness 55-57 HRC, we can highly appreciate the achieved notch toughness value (**Tab. 5.3** and **Tab. 5.4**), even with the above mentioned content of carbon and carbide-forming elements Mo and W in particular samples from modified trial heats.

Heat	Heat treatment, quenching/tempering	Hardness HRC	KCU 2 J/cm2
7	1,060°C/oil/590°C	52.3	33.3
8	1,060°C/oil/605°C	51	19
9	1,060°C/oil/590°C	57.1	33.3

Tab. 5.4 Hodnoty vrubové houževnatosti při teplotě 450 °C

Tab. 5.4 Notch toughness tests at elevated temperature of 450 °C

In the sequence of chemical composition of the mentioned alloying elements, the task of wolfram is to increase resistance to wear at reduced molybdenum content, and to intensify abrasive wear resistance at the same time.

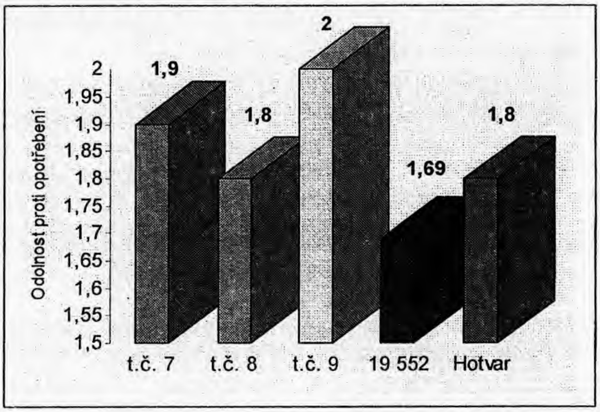
The achieved results of abrasive wear resistance of individual modifications experimental heats, together with the results of trial heats of 19 552 grade tool steel and „HOTVAR“ grade tool steel made by UDDEHOLM company are shown in **Fig. 5.1.**

Positive results of mechanical properties values in the sphere of hardness and, subsequently, abrasive wear resistance were reached by a suitable modification of heat no. 7 chemical composition. Heat no. 8 results have not quite picked up on a supposed trend of rising mechanical properties values. The third modification – heat no. 9 reached the highest values of hardness and abrasive wear resistance.

6. ACHIEVED RESULTS AND CONCLUSION

- Regarding very good achieved results of the required values in the sphere of hardness and abrasive wear heat no. 7, the next optimization process is likely to be based on this steel modification chemical composition.
- Microscopic inspection of a heat no. 8 sample was performed on a cross-sectional scratch pattern of the forged bar axis area. The material was markedly impurified by complex nonmetallic inclusions – nonworkable silicates, which may negatively influence the monitored mechanical values. Further metallurgical measures will be implemented while making repeated modification no. 8 heat.
- Maximum results in the sphere of hardness and abrasive wear resistance values reached from the heat no. 9 modification material will have to be assessed with regard to charge raw materials costs.

- For the purpose of running tests realization, it will be essential to consider relations of very favourable mechanical properties, production economy of particular heat modifications related to assumed operational number of work strokes into a forging die.
- After assessment of the most advantageous trial heat modification, the experimental heat will be made in 1.7 t medium-frequency electrical induction furnace. Following the after forging and heat treating, the material will be verified in operation in the final form of the forging die.



Obr. 5.1 Odolnost proti abrazivnímu opotřebení [ψ_a] jednotlivých zkušebních taveb

Fig. 5.1 Abrasive wear resistance [ψ_a] of individual trial heats

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